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The choice of primary colours for colour television

No. 1970/32

Research Department, Engineering Division
THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

THE CHOICE OF PRIMARY COLOURS FOR COLOUR TELEVISION

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(PH-65)

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THE CHOICE OF PRIMARY COLOURS FOR COLOUR TELEVISION

Summary

The chromaticities of the colour phosphors used in the receiver display tube are a fundamental part of the specification of a colour television system and the colorimetric design of a camera or film scanner cannot be undertaken without this knowledge. The chromaticity co-ordinates specified by the NTSC in 1953 now have little practical meaning since phosphors have changed considerably and signal originating devices are designed to suit current production displays. A U.K. Working Party, set up under CCIR National Study Group 11, examined the situation in the United Kingdom and made recommendations that led to a change in the specified receiver chromaticities for PAL System I. The reasons underlying this change are discussed together with the advantages and disadvantages of alternative proposals.

1. Introduction

Most colours occurring in nature can be matched metamerically by the addition of three suitably-chosen primary colours. A few, however, cannot be matched by means of a simple additive mixture and it is necessary to describe the match as being between a mixture of the unknown colour with one of the primaries on the one hand and a mixture of the remaining two primaries on the other. In this case the amount of the primary mixed with the unknown colour is considered as a negative quantity. All colours can be matched with any three primaries if negative quantities are included but in practice the three colour primaries of an additive system are usually chosen to minimise the occurrence of negative quantities.

In a colour television system the gamut of colours which may be reproduced is limited to those falling within a triangle drawn on the C.I.E. chromaticity diagram, the apexes of the triangle being the chromaticities of the three primaries. The choice of primaries for a colour television system is essentially limited by colorimetric considerations of the spectral characteristics and efficiencies of available phosphor materials and this has always been the case. It is, of course, obvious that the colorimetric design of a colour television camera which is required to analyse the scene into its colour components and produce colour separation signals for transmission is primarily determined by the chromaticities of the reproducing primaries available at the receiver.

In the period 1949 – 1953 the National Television System Committee of the United States of America gave serious consideration to the choice of suitable primaries for a colour television system. The literature of that period contains a number of proposed sets of chromaticity co-ordinates based mainly upon the silicate phosphors which were at that time the only suitable ones available. By September 1951, Panel 7 of the N.T.S.C. had recommended a set of primary chromaticities; these were promulgated publicly by the N.T.S.C. on 2nd February 1953 and were reiterated in the Report of the Chairman (Mr. A.V. Loughren) of Panel 13 of the N.T.S.C. dated 8th July 1953. This document states:

> 'The gamma corrected voltages E_R', E_G', and E_B' are suitable for a color picture tube having primary colors with the following chromaticities in the C.I.E. system of specification:
>
> | | x | y |
> |---|---|---|
> | Red (R) | 0·67 | 0·33 |
> | Green (G) | 0·21 | 0·71 |
> | Blue (B) | 0·14 | 0·08 |
>
> and having a transfer gradient (gamma exponent) of 2·2* associated with each primary color** (18th meeting, Motion 9).'
>
> * At the present stage of the art it is considered inadvisable to set a tolerance on the value of gamma. This portion of the specification will not be enforced pending a further determination thereof.'
>
> ** The voltages E_R', and E_G' and E_B' may be respectively of the form of $E_R{}^{1/\gamma}$, $E_G{}^{1/\gamma}$ and $E_B{}^{1/\gamma}$, although other forms may be used with the advances in the state of the art.'

2. Colour fidelity

The optimum colour reproducer would use primaries so chosen that lines joining their C.I.E. co-ordinates encompassed the most important part of the area of the C.I.E. colour diagram. Suitable primary colours were suggested by Hardy and Wurzburg[1] but regrettably cathode ray tube phosphors having this performance with suitable efficiency have yet to be discovered. It was pointed out in an appendix written by D.W. Epstein[2] to the petition of RCA before the Federal Communications Commission dated 25th June 1953, that for good colour reproduction it is necessary that the tristimulus values or trichromatic coefficients of the subject and of the reproduction be the same.* In order to reproduce faithfully all those chromaticities of the original scene which lie within the colour triangle of the receiver primaries, it is necessary to control properly the relative amounts of the primaries at every point of reproduction. This imposes special requirements on three spectral sensitivity curves that are used in the camera for making the trichromatic analysis of the original scene. The theoretically-required camera sensitivity curves have regions where the sensitivity is negative. D.W. Epstein goes on to show that any departure from the camera spectral sensitivity, as calculated for a given set of receiver reproducing primaries, must result in some lack of fidelity. The negative portions of the ideal camera spectral sensitivity curves depend rather critically on the choice of receiver primaries but the positive portions may vary only slightly for a wide choice of receiver primaries.

Although all this was understood and so clearly documented very early in the history of colour television, successive designs of colour television display tube paid very little heed to the matching of the colour display with the camera analysis. For more than ten years following the publication of the N.T.S.C. specification in 1953, it was probably of minor importance that the manufacturers of shadow-mask tubes chose phosphors more on account of their brightness than on account of their conformity with N.T.S.C. chromaticities. During this period the effective spectral sensitivity of television cameras was limited to the positive portions of the ideal responses and the errors present because of this limitation were not substantially changed by making changes in the chromaticities of the display phosphors. However, the introduction of the linear matrix[3] into the practical design of colour television cameras has meant that they are now given an effective spectral sensitivity which includes an approximation to the negative sensitivities as well as the positive portions of the curves and although the overall fidelity of the television system has been much improved, the importance of a match between the camera and the receiver has become much more pronounced.

Reference to Fig. 1 shows the extent to which the chromaticities of shadow-mask tube phosphors have changed since 1953. Each move to achieve a greater brightness has resulted in a reduction of the gamut of colours which may be reproduced. Some of these were not necessarily bad exchanges since the subjective excellence of colour reproduction must include an adequate luminance level and improvements in brightness were initially more important than the ability to portray extreme colours.

The way in which the camera has followed the changes in reproduction primaries appears to have been rather haphazard. As already stated, a camera having positive-only effective spectral sensitivity characteristics is not particularly critical of discrepancies between its effective spectral analysis and the chromaticity co-ordinates of the phosphors used in the display tube in the receiver, but when linear matrix techniques are employed this becomes very much more important. The coefficients for the linear matrix have to be computed and chosen with considerable care since they exercise a powerful total effect upon the colorimetry of the system and indeed are at least as important as the shapes of the positive portions of the characteristic. Generally speaking, matrix values have been calculated and verified experimentally by reference to the chromaticities of phosphors used in the colour television monitors which happened to be in existence at the time of the choice. Hence, almost none of the colour television cameras at present in service with broadcasting organisations throughout the world conform to the original N.T.S.C. chromaticities but are based in an imprecise manner upon some other values more or less relevant to an existing colour monitor. Furthermore, the effective colorimetric performance of any given television camera must be considered not only on its spectral analysis characteristic and the linear matrix of its primary signals but also upon the gamma and the white point of the signals as transmitted.

It is therefore not correct to suggest that the chromaticities originally specified by the N.T.S.C. in 1953 have remaining relevance and the regrettable fact is that our present colour television cameras cannot be said to conform to any uniform specification at all.

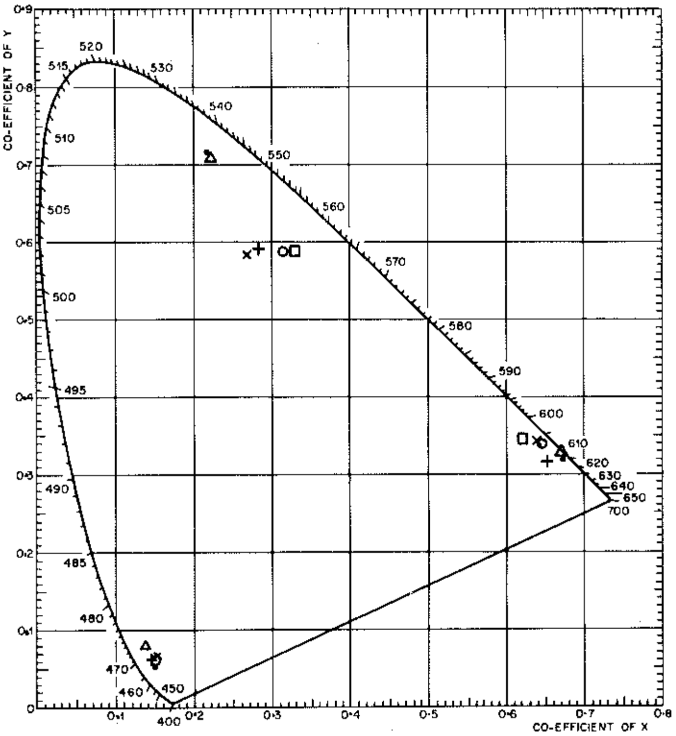

Fig. 1 - Receiver chromaticity co-ordinates

△ NTSC primaries 1951-53
▪ Phosphate phosphors circa 1953
× Sulphide phosphors
+ Rare Earth 1968
○ Current production 1969-70
□ Complementary shift phosphors 1970-71

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* Although this is fundamentally true, it does not take into consideration some of the practical circumstances in colour television practice which arise when the viewing conditions of the original scene and of the reproduction are different e.g. luminance level, picture surround, white point, scale size etc.

3. United Kingdom proposal

Recognising the unsatisfactory state of affairs wherein colour television cameras used in broadcasting were not colorimetrically related to receivers by anything other than a somewhat empirical approach and that the 1953 N.T.S.C. specification was obsolete in respect of receiver and camera colorimetry, a Working Party, set up by the United Kingdom CCIR National Study Group 11, Sub-group 11A, undertook a study of the situation. It was found that although the trichromatic coefficients of the shadow mask phosphors had moved quite a long way from those of the original N.T.S.C. specification, receivers in current production and the great majority of receivers being used by the public had reproduction primaries falling within a fairly small group of characteristics as plotted on the C.I.E. chromaticity diagram. It therefore seemed rational to examine the spread of chromaticities in normal use and the effects of this spread upon the fidelity of the reproduced picture when the camera had been designed to match a given receiver.

It was not considered sufficient merely to find some mid-point in the chromaticities of existing receivers and to base the colorimetric design of the camera upon that. It was felt that provision should be made as far as possible to take advantage of future improvements in phosphors and this involved some prediction of the course that these improvements might take. The problems were discussed with major producers of colour phosphors and shadow mask tubes and their advice was sought on the choice of a set of chromaticity co-ordinates to be used for camera design such that they would not be too far from those of existing receivers and yet were strategically placed to take advantage of possible improvements in phosphor technology. The willing co-operation of the organisations consulted, both with the Working Party and with each other, made possible an agreement on a chromaticity specification which could be adopted for PAL colour television System I.[4] This was as follows:

TABLE 1

Chromaticity Co-ordinates for PAL System I

	x	y
Red (R)	0·64	0·33
Green (G)	0·29	0·60
Blue (B)	0·15	0·06

Receiver white point: Illuminant D_{65}
Gamma* of RGB displays: 2·8

Reference to Fig. 2 will show the relationship between typical receiver phosphors and the points chosen as the design-basis of cameras to be used in the U.K. television broadcasting.

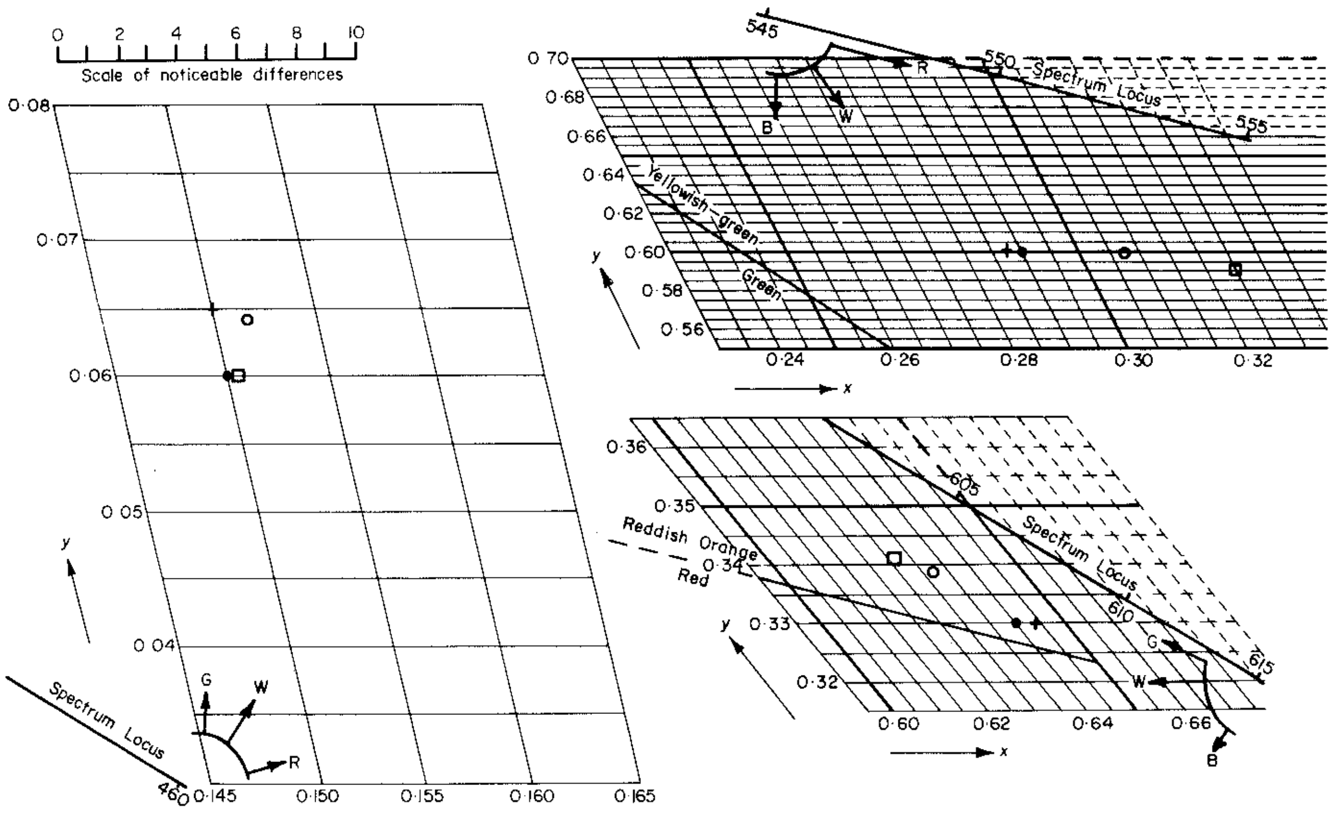

Fig. 2 - Uniform chromaticity chart for colour TV primaries

● PAL System I	o Receiver phosphors 1969-70
+ Receiver phosphors 1968	□ Complementary-shift phosphors 1970-71

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* It should not be assumed that the gamma of the transmitted signals would be 1/2·8. In practice a value of approximately 0·45 is found to give subjectively the best overall contrast law for average television viewing conditions.

4. Performance appraisals

It was of course necessary to examine, by calculation and by subjective test, the performance of this camera when used in conjunction with a number of existing, practical display tubes. The colorimetric performance resulting from a given relationship between the chromaticity characteristics of the camera and those of the receiver can be calculated for each set of circumstances and it is also possible to set up practical experiments to permit subjective judgements. Accordingly the Working Party set out to determine the importance of discrepancies between the effective analysis characteristic of the camera and the reproduction primaries. These were examined over the spread of receivers known to be in existence: if the discrepancies between the camera and the phosphor chromaticities were too great, then the colour fidelity of the system overall would be found to be significantly degraded. At the same time however it was clearly realised that it is possible for the broadcaster to choose only one set of receiver primaries as a basis for the transmission and that all other receivers not having those primaries must display a less accurate picture, although the loss in fidelity might be so small as to be negligible.

4.1. Camera designed for PAL System I primaries with existing receiver phosphors

A camera whose colorimetric design was based upon the PAL System I receiver chromaticities was, in the first instance, considered in conjunction with three different types of receiver display phosphors. One set of receiver phosphors considered was close to the PAL System I chromaticities and was representative of the rare earth phosphors generally in use in 1968. A second set of phosphors was suggested by shadow mask display tube manufacturers as being representative of current production in 1969–1970 while a third set of phosphors used was typical of those proposed for production in 1971. In the latter case a complementary shift of the chromaticities of the red and green phosphors had been employed: this is found in practice to permit a much greater shift of both the red and the green points for a given degradation of the picture than would have been possible had only one of the two points been moved. The complementary shift, although reducing the size of the triangle of possible colours, does not cause the severe distortion of skin tones which is noticed when, for example, the green phosphor is moved in the direction of yellow, while the red is unchanged. Chromaticity points relevant to the considerations are given in Table 2.

TABLE 2

Chromaticity Co-ordinates of Typical Phosphors in Current Use

	Red		Green		Blue	
	x	y	x	y	x	y
1968 Rare earth	0·644	0·330	0·288	0·600	0·150	0·065
1969–70 Current Production	0·632	0·339	0·307	0·597	0·152	0·064
1970–71 Complementary Shift	0·627	0·341	0·325	0·590	0·150	0·060

The Working Party and several groups of observers, totalling 20 observers in aggregate, then appraised the colorimetric performance of the system under the three sets of conditions (1) when the receiver phosphors were a very close match for the camera design (2) when the current production tube was in use and (3) when the proposed complementary shift group of phosphors was in use. A number of different types of skin tones were appraised, together with a number of general scenes and a flag containing the EBU standard fabrics.[5] The results using the EBU Quality Scale* for subjective grading are given in Table 3 below:

TABLE 3

Subjective Grading of Typical Phosphors (EBU Quality Scale)

	Skin Tones	General Scenes	Saturated Colours
1968 Rare earth phosphors	1·2	1·3	1·2
1969–70 Current production	2·1	1·3	1·5
1971 Complementary shift	3·0	1·3	2·0

It will be seen that the effect of discrepancies between the camera and the phosphors was reflected in the observers' judgements of colour quality but that so far the error had not assumed serious proportions. It therefore remained to be established whether much greater discrepancies between the camera and the receiver could be tolerated.

4.2. Other proposed cameras with existing receiver phosphors

It was thought that it would be interesting to observe the effect of basing the calculation of colour analysis and matrix coefficients for a modern colour camera upon the original N.T.S.C. chromaticities. It was also noted that the proposal made by the Netherlands and tabled at the meeting of CCIR Study Group 11 in Geneva, September 1969[6] had suggested a compromise between the original N.T.S.C. specified chromaticities and those of a typical 1968 colour television receiver. The Working Party then examined the colour performance of three different cameras when they were used in connection with existing receiver phosphors. The camera characteristics were based upon:

(1) The values for PAL System I
(2) The Netherlands compromise proposal
(3) The original N.T.S.C. chromaticities 1953

The values of these chromaticity co-ordinates are shown in Table 4.

In the practical experiment, only a single colour monitor was used, equipped with current (1969/70 production) phosphors which were intermediate in the previous set of tests between the 1968 rare earth phosphors and the proposed shifted red/green for 1971 production. All three

*EBU Quality Scale

1 Excellent
2 Good
3 Fairly Good
4 Rather poor
5 Poor
6 Very poor

TABLE 4

Chromaticity Co-ordinates upon which the Colorimetric Design of the Camera was Based

	Red		Green		Blue	
	x	y	x	y	x	y
PAL System I Camera	0·64	0·33	0·29	0·60	0·15	0·06
Netherlands Proposal	0·66	0·33	0·25	0·65	0·145	0·07
N.T.S.C. Specification	0·67	0·33	0·21	0·71	0·14	0·08

camera conditions were examined in random order on the single monitor, using once again a wide variety of skin tones with some general scenes and the EBU test fabrics. The results were as follows:

TABLE 5

Subjective Grading of Camera Performances (EBU Quality Scale)

	Skin Tones	General Scenes	Saturated Colours
PAL System I camera	1·9	1·2	1·2
Netherlands Proposal	4·3	3·2	2·9
N.T.S.C. Specification	4·6	4·1	3·4

These indicate that a change in the trichromatic coefficients used for the camera design from those that are near to a typical receiver to those that are based upon the original N.T.S.C. phosphors or to the Netherlands compromise proposal will cause an unacceptable degradation of the picture.

Hence it would seem from the results of this experiment that it is fortunate that camera manufacturers have disregarded the N.T.S.C. specification for chromaticity and have based their camera designs upon a realistic assumption of the chromaticities of modern colour television receivers.

5. Consideration of results

It is necessary at this stage to consider whether the results of calculation, supported by a subjective test are sufficient evidence upon which to base a decision concerning the chromaticity coefficients to be adopted in the specification of the colorimetric design of a television camera. It should be noted that in the subjective tests described in the previous chapter, the monitors were in every case lined up to track accurately over the grey scale balanced to Illuminant D_{65}. Furthermore the saturation control of the decoder was set up in accordance with the established practice for broadcast quality monitors using a carefully calibrated colour bar test signal. Given that the object of colour television broadcasting is to provide for the viewer an acceptable picture for the majority of subjects transmitted, rather than aiming only at objective accuracy, it might be possible to adopt some set of chromaticity characteristics for the camera other than those related to existing receivers in the hope that the viewer would, by misadjustment of the chroma-control and the white point of the receiver, achieve subjectively satisfactory skin tones which are, after all, the most sensitive indications of poor colour fidelity. Such a step would, however, by the inclusion of a subjective receiver balance, undermine the ability of the broadcasters and the receiver manufacturers to achieve an engineering specification for colour reproduction. A practical examination of proposals to re-adjust balance and saturation of the receiver shows that they are not, in fact, acceptable remedies. With a camera designed to suit N.T.S.C. chromaticities and a modern receiver, an increase of approximately 45% in chrominance signal level is found necessary to bring the saturation of colours subjectively into the right area and this would have serious implications on the effect of interfering signals, cross-colour, and service area. With a camera designed in accordance with the Netherlands proposal, the corresponding increase in chrominance signal level is about 40%. Moreover the shift of white point required to make skin tones relatively acceptable renders many other colours noticeably incorrect.

Any attempt to adopt chromaticity coefficients for the camera which were not close to practical, realisable phosphors would in any case cause great difficulty to the television broadcaster. Even if the empirical re-adjustment of colour balance and saturation could be tolerated and achieved in a retrospective operation concerning the 1·5 million receivers already installed in Europe, such a procedure would be quite intolerable in broadcasting control rooms. A standard and objective method of setting up monitors and cameras is essential and it would be necessary either to have control room monitors with phosphors to match the chosen characteristics for the camera or alternatively it would be necessary to fit each monitor with a matrix. An operation upon the gamma-corrected signals can only give approximate correction and a rigorous treatment would require three linearising circuits for the decoded colour separation signals, followed by a linear matrix and three gamma-correcting circuits. The likelihood of such an arrangement proving economical or satisfactory seems very remote.

At the same time, however, the Working Party have been anxious not to overlook the fact that a set of phosphors giving a larger gamut of reproduced colours than those in current production and also having good efficiency, might one day be devised.

6. Possible courses of action

It might be argued that the present situation in Europe is relatively satisfactory and that no action is necessary. The spread of chromaticities in receivers at present being offered to the public appears to be sufficiently small to give no serious degradation of the pictures transmitted from a typical modern television camera. Any new receiver appearing on the market would be judged by its performance when used in connection with existing broadcasts and any new camera would likewise be judged by its performance when used in connection with existing receivers. Existing specifications of standard chromaticity co-ordinates would remain notional and of no practical significance.

The excellence of the PAL system in giving freedom from colour errors arising in the transmission path relieves the viewer of any need to make adjustments to colour balance or hue on changing from one station to another. It is therefore very desirable that all broadcasting networks which may be received by any particular receiver should have uniform chromaticity characteristics in their output signals. This means that the networks should use identical colour monitors for balancing their transmissions and have totally objective methods of lining up both the monitor and the camera. Furthermore, all cameras must have their analysis characteristics and matrix coefficients based upon a recognised set of reproduction primaries. Hence it is very desirable to have a meaningful and rigorously observed standard of transmission from the point of view of colorimetry in any country where there is more than one network. The same argument could be extended to all countries taking part in the Eurovision network.

If it is decided that some action should be taken, then the possible courses are as follows:

(1) The U.K. proposal, as adopted in PAL System I, to base the colorimetric design of the camera upon chromaticities near to those of existing receivers, or alternatively,

(2) To adopt chromaticity co-ordinates for the camera design which are not related to existing receivers but describe a set of phosphors not yet invented which would be more satisfactory from the point of view of colour gamut and efficiency than those existing.

The advantages of Course (1) are:

(a) that it gives the best possible picture on all existing receivers

(b) that practical standard colour monitors can be used in broadcasting control rooms to assist in ensuring a standard output from all networks

(c) that it is substantially in line with existing practice and therefore requires no expensive re-equipment.

The disadvantage of Course (1) is that in the event of a new set of phosphors being invented which gave a greater gamut than those for which the camera is designed, incomplete advantage could be taken of this improvement. The implications of this are dealt with in a companion paper.[7]

The advantage of Course (2) is that any new set of phosphors invented might be closer to the chosen chromaticities than those adopted under Course (1) and the door is not closed to this improvement. The disadvantages of Course (2) are:

(a) that it will not be possible to obtain practical control room monitors having phosphors to match the chromaticity co-ordinates chosen for the camera design

(b) that the picture quality on all existing receivers will be degraded even though steps are taken to readjust the receivers for colour balance and saturation

(c) the ability to have objective setting-up methods has been lost

(d) the precise direction and magnitude of any improvement of phosphors is not predictable and hence the new values chosen for the chromaticity co-ordinates can only be guesswork.

7. Conclusions

In making its original recommendations, the Working Party of U.K. CCIR Study Group II, Sub-group 11A concluded that:

(1) It was desirable to revise* the specification for the chromaticity co-ordinates of PAL System I colour television to ensure uniformity between networks

(2) the existence of a very large number of colour receivers having substantially similar chromaticity characteristics weighed heavily in favour of choosing co-ordinates to give the best possible picture on these receivers

(3) there was no indication of any receiver becoming available which had reproduction primaries substantially different from those of existing receivers. It was noted that any receiver having very different colorimetric characteristics would inevitably be incompatible with those existing and the broadcaster could do no more than choose one set of chromaticities for his transmission

(4) it is important that broadcasters should have uniform colour monitors which were a good match for the chromaticity characteristics chosen for the camera, hence the necessity of choosing camera characteristics which are related to practical monitors

(5) the choice of chromaticities for a camera not related to existing receivers or monitors must inevitably result in down-grading the picture quality obtained by existing receivers

(6) the likelihood of being able to estimate accurately chromaticity co-ordinates of a new set of phosphors yet to be invented is very small and the advantage of the immediate adoption of any estimated value in advance of their realisation is minimal

(7) in the event of a new set of phosphors being invented which were substantially better than those in existing receivers it would then be possible to reconsider the specification of cameras and at an agreed date change to the new specification. In this way Course (2) would then be implemented without, in the meantime, degrading the performance of all existing receivers but with the advantage of knowing precisely what chromaticity co-ordinates should be adopted to match the new phosphors.

* This resulted in the phosphor specification given in Reference 4.

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9. Constitution of the Working Party

The members of the Working Party set up by Sub-group 11A of U.K. National CCIR Study Group 11 were:

Mr. B.R. Rogers	BREMA (Rank-Bush-Murphy)
Dr. G.B. Townsend	ITCA (Thames Television)
Mr. M.S. Tooms	ITA
Mr. C.B.B. Wood, Chairman,	BBC

In addition, Mr. W.N. Sproson, BBC Research Department, was co-opted to give advice on the theoretical aspects of colorimetry. Messrs. W.W. Wright and G.C. Playford of Thorn Colour Tubes Limited collaborated in experiments, measurements and the supply of experimental prototype tubes, while Messrs. T. Jacobs and A. Ciuciura of Mullard Limited, Mr. C.W. Thierfelder of RCA Corp. and many others were also consulted.

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